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Computerized Video Densitometry Method for Rapid Analysis of Infrared Photographic Images

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Summary

A method has been developed for the rapid analysis of thermal data. It automates a previously developed manual method. Input data for both methods are provided in the form of infrared photographs of heated surfaces. The manual method, called the microdensitometry method of infrared photographic pyrometry, uses a flat-bed microdensitometer to measure relative film density. A calibration technique allows the conversion from film density units to corresponding temperatures.

The automated method, called computerized video densitometry, uses a video film scanner and on-line computer processing. Hardware was available in the form of an existing image analysis system. A new procedure based on the manual method was developed, and computer programs were produced to control the hardware and to process and file the data. The resulting system increases the speed of data reduction by a factor of approximately 50 at no apparent sacrifice of accuracy. Determination of the temperature distribution across a heated gas turbine blade was used to test the methodology and the procedure.

Introduction

Infrared photographic pyrometry is a method for determining the temperature distribution across a heated surface. It was developed at the NASA Lewis Research Center as part of a program to develop advanced, cooled blades for aircraft gas turbines. In this method photographic records are made with infrared-sensitive film. A densitometer is used to measure the film density at any desired point, and a calibration procedure produces the corresponding temperature. The method is described fully in reference 1. This method was selected because it offers the following advantages over contact methods, optical pyrometry, and infrared scanning devices:

(1) It does not influence the temperature distribution, as do contact methods.

(2) It produces a full-field measurement, as opposed to the discrete-point measurements produced by contact methods and optical pyrometry.

(3) It has a much higher recording speed and much better spatial resolution than infrared scanning devices.

(4) It produces photographic records, which are both easily accessible and suitable for archival storage.

The method suffers from two major disadvantages:

(1) Data reduction is quite slow. About 1 hour is required to analyze a reasonable number of points (i.e., 25 to 50) from a single photographic frame.

(2) The results are sensitive to operator error. There is a measurable variation between the results produced in successive trials. The variations appear to be the result of poor location of the origin of the coordinate system.

As another phase of the turbine-cooling development program, it was desired to produce a thermal history of several turbine blade configurations. The blades were to be subjected to a heat-hold-cool thermal cycle. Temperature measurements were to be made of the entire blade surface at frequent intervals. The large number of temperature measurements precluded the use of the microdensitometer and the manual method. Three different blade configurations were to be investigated. Each side of each blade configuration was to be analyzed. Infrared photographs were made at 1-second intervals over a 240-second test run. This resulted in 1440 film frames to be analyzed, a task requiring about 1000 man-hours of labor.

The primary reason for using an automatic method was to reduce the labor time by at least one order of magnitude. Secondary reasons were to develop a method that could be used by less-skilled personnel and one that yielded more accurate and reproducible results.

A survey of the literature and of commercially available systems revealed no existing method that would meet the objectives. Therefore a system was developed at the NASA Lewis Research Center. The system was developed from an existing image analysis system used for another purpose (ref. 2). In this method the source of data is still infrared photographic records. But the records are scanned by a vidicon camera, and the output is fed to a computer-based image analysis system. A special calibration scheme was developed and programmed for the computer. Each film frame is scanned by the vidicon, and the data are processed on line. Temperatures are printed on the computer terminal at each of several preselected coordinates on the turbine blade. These data are also recorded on magnetic tape for future processing by other computer pro-

grams. Use of the data in a life-prediction analysis is foreseen. The procedure is approximately 50 times faster than the manual method, with no apparent sacrifice in accuracy. The equipment can be operated by a technician with little special training.

This report describes the development of the computerized video densitometry method and the logic of the computer programs and compares the results obtained with those produced by the infrared photographic pyrometry method for a representative turbine blade.

Symbols

- *d* relative film density
- *E* relative radiant energy
- *k* undefined constant
- *T* temperature
- Δ difference between reference values of relative film exposure energy and relative radiant energy
- ϵ relative film exposure energy
- λ wavelength

Subscript:

- *r* reference value

Microdensitometry Method of Infrared Photographic Pyrometry

The microdensitometry method of infrared photographic pyrometry is described in detail in reference 1. Its application to a turbine-cooling study on simulated turbine blades is described in reference 3. It is reviewed briefly in this section, with emphasis on the basic elements underlying both the manual and automatic methods.

Infrared photographic pyrometry uses infrared-sensitive photographic film as its sensing element. It is distinguished from conventional infrared film imagery by its quantitative nature. Conventional infrared film imagery reveals regions of various temperatures over the field of view of a photographic image. However, it does not contain enough information to provide quantitative values of the various temperatures recorded.

Infrared photographic pyrometry supplies two items of information in addition to the photographic image. These two items of information define the film response characteristic and relate it to the temperature of a radiating body. That information coupled with the film density at a given point produces the temperature at that point. The film density must be acquired from either a microdensitometer or a video densitometer. A computer-automated image analysis system is described in reference 2. That system was used as a video densitometer for this project.

The common elements of the two systems are described in this section. Those elements unique to the video densitometry system are described in the next section.

Relative film density depends not only on the value of incident radiation, but also on the film processing parameters. As a practical matter, film processing from roll to roll cannot be expected to remain constant enough to provide the reproducibility required for pyrometric applications. In addition, film response varies between various emulsion batches as well as with aging. Therefore, for a testing program that requires more than one roll of film, calibration information must appear on each roll. This has the additional benefit of eliminating any other system variables from roll to roll.

Calibration information is introduced to each roll of film by using a calibrated photographic step tablet. The step tablet is uniformly illuminated by a light source of controlled intensity in a sensitometer. The step tablet relates film density to relative radiation intensity. This relationship is termed "the film response function" and is illustrated in figure 1. The only remaining problem is to relate radiation intensity to temperature. This relationship is termed "the radiation function." The relationship between surface temperature and surface radiant energy can be calculated from Planck's fundamental blackbody law (ref. 4).

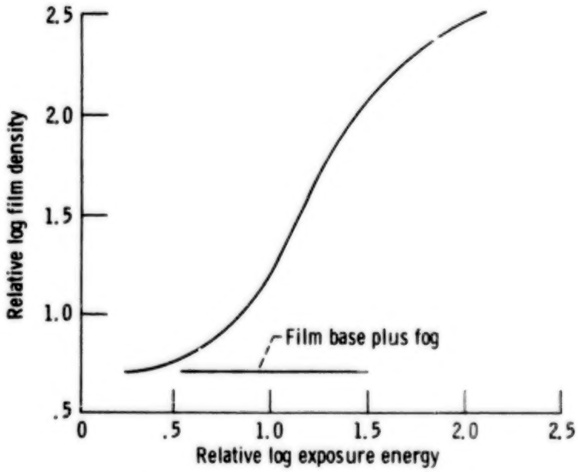
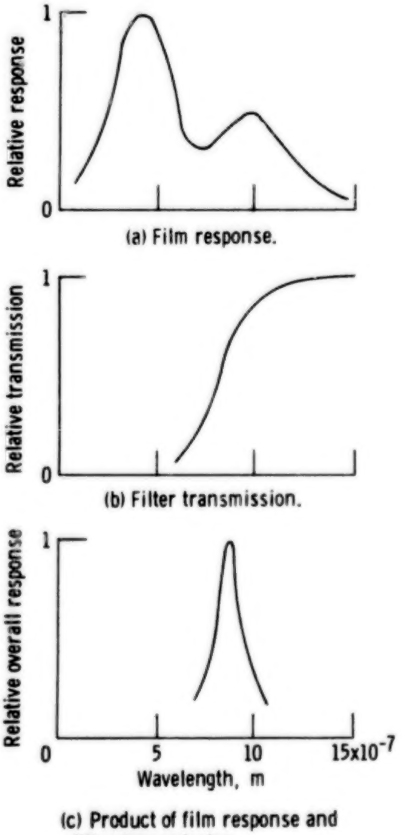


Figure 1. - Typical film response function for an arbitrary development process.

$$E(\lambda) = k_1 \lambda^{-5} / (e^{k_2/\lambda T} - 1)$$

$$\therefore\ E = \int_{\lambda_1}^{\lambda_2} \left[k_1 \lambda^{-5} / (e^{k_2/\lambda T} - 1) \right] d\lambda$$

where e is the base of the natural logarithm, 2.71828. Although that relationship is for blackbodies and the emissivity of the heated surface is less than blackbody emissivity, only the change in temperature with radiation is required. The change in temperature with radiation is independent of emissivity. Therefore the simpler blackbody formula can be used for convenience. The integral can be performed numerically from the spectral energy density function. That function can be determined by multiplying the relative transmission of the infrared filter on the camera lens by the relative film sensitivity at each desired wavelength. Figure 2(a) represents a typical relative-film-sensitivity response function, and figure 2(b) represents a typical filter-relative-transmission function. Their product, which represents the range of integration, is illustrated in figure 2(c). Because



(a) Film response.

(b) Filter transmission.

(c) Product of film response and filter transmission.

Figure 2. - Exposure energy on film (idealized representations).

the actual value of radiant energy is immaterial, it is expressed in arbitrary units. These arbitrary units were chosen to match the steps of the calibrated stepped-exposure scale used in determining the film response function. Since a photographic stop is a doubling of light energy, the basic unit was chosen as a doubling of energy. For this application each step was a half stop, so the step increment is $\sqrt{2}$. Thirty such arbitrary units were used in a temperature range of approximately 540° to approximately 1300° C. The radiation function is illustrated in figure 3.

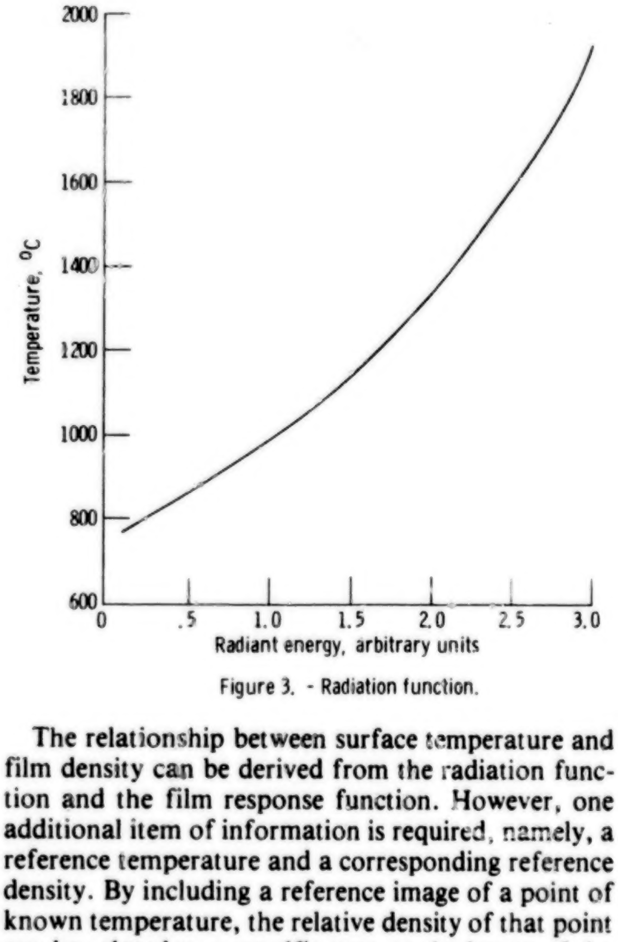


Figure 3. - Radiation function.

The relationship between surface temperature and film density can be derived from the radiation function and the film response function. However, one additional item of information is required, namely, a reference temperature and a corresponding reference density. By including a reference image of a point of known temperature, the relative density of that point can be related to a specific step on the image of the calibrated step tablet, as follows.

It is apparent that the relative exposure energy required to produce a given film density can be obtained from the film response function. Similarly, the surface temperature required to produce a given radiant energy can be obtained from the radiation function. However, the relationship between relative film exposure energy and relative radiant temperature is lacking. That relationship is provided by the aforementioned reference temperature and corresponding reference density.

One image must be produced that has a point of known temperature. It is most convenient to allow

the test object to reach steady state and to measure the temperature at a specified point. In this case an optical pyrometer was used. This in effect alines the two abscissas, as described in reference 1. The density of the image at that point is measured, and its corresponding step on the image of the step tablet is determined. Once the two functions have been alined, the procedure becomes the following:

(1) Measure the film density at a given point
(2) Determine the corresponding relative radiation intensity from the film response function
(3) Determine the corresponding temperature from the radiation function

The process is illustrated schematically in figure 4.

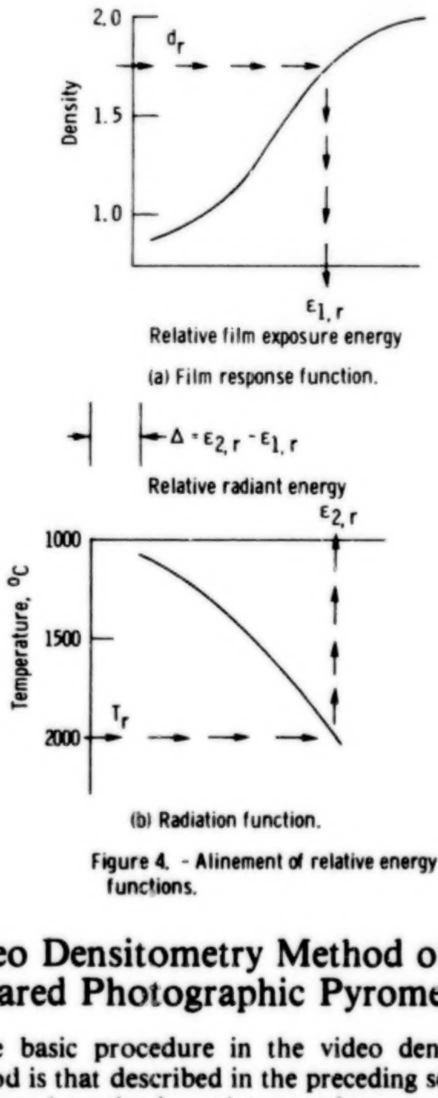


Figure 4. - Alinement of relative energy functions.

Video Densitometry Method of Infrared Photographic Pyrometry

The basic procedure in the video densitometry method is that described in the preceding section. In reference 1 a point-by-point procedure was used. The film density was measured on a microdensitometer. The film response function and the radiation function were presented as graphs, and the conversion from density to temperature was performed manually. The variation of the procedure described herein follows the same steps but substitutes a television image system for the densitometer, computer storage for the graphs, and electronic computation for the manual procedure. This computer-based television imaging system is described in detail in reference 2. A brief overview follows. The logic of the computer program is briefly described in the appendix.

A precision film-transport mechanism indexes each frame of the film strip in register over a properly masked light box. Scanning is performed by a special vidicon television camera tube and a special circuit that were selected for photometric accuracy. The raw data are the brightness values transmitted through the film by the illuminator. Scanner output is amplified logarithmically, in accordance with the definition of density as the logarithm of the reciprocal of the film transmission factor. The amplifier-scanner output is then digitized and stored on a magnetic disk.

The image is stored as 490 interlaced lines, each consisting of 512 eight-bit picture elements. Each picture element represents one of 256 possible grey values from black (0) to white (255). The image is redisplayed on a television monitor. The location of any given point is obtained either from calculated coordinates or from reading the coordinates of a joystick-operated cursor that is displayed as a blinking dot on the monitor.

Initial values of the program parameters are defined in three steps. First, the coordinates at which the temperature is desired are defined by the cursor. Second, the film response function is defined as described subsequently, and reference values of temperature and density are similarly obtained. Third, following this initialization procedure, images of the turbine blade at various stages of its heating and cooling cycle are introduced. The output is produced completely under computer control without additional operator intervention.

The film response function is produced as a table of data by the computer program. Several steps in the image of the exposure scale are digitized. Film density is measured at several points on each step, averaged, and stored in the table. An arbitrary number of points is defined by the cursor, and the procedure is repeated until the densities on all the steps have been stored.

The 24 steps on the stepped-exposure scale are capable of producing a log density range of 3.6. However, the image on the film can discriminate between only about 19 of them, for a log density range of 2.5. Because of the nonlinear film response curve, the log density range produced on the film image is, at greatest, 2.2.

The radiation function does not change with the various data to be processed or with the varying input parameters to the controlling computer program. Therefore it was evaluated independently, and its values were compiled into the computer program as an unvarying table. Its form has already been referred to in figure 3.

Just as in the manual photographic pyrometry method, there must be a known reference temperature and reference density. This information is used to aline the film response curve and the radiation curve, as discussed in the preceding section.

In the video densitometry method the reference temperature is an input parameter to the controlling computer program. The reference density is obtained from the image of the turbine blade at steady state. That image is digitized, a portion of the image is scanned, and the maximum density in that region is assigned to the reference temperature. The information is then used as described in the preceding section. The reference temperature and density are stored by the computer program.

Assume that the reference film density d_r produces a value of relative film exposure energy $\epsilon_{1,r}$ from the film response function. Assume that the reference temperature T_r produces a relative radiant energy $\epsilon_{2,r}$ from the radiation function. Let $\Delta = \epsilon_{2,r} - \epsilon_{1,r}$. The temperature T corresponding to any other value of film density d can be found as follows:

Find the value of relative film exposure ϵ_1 corresponding to the density d from the film response function. Find the corresponding value of relative radiant energy ϵ_2 by adding Δ.

$$\epsilon_2 = \epsilon_1 + \Delta$$

Find the temperature T corresponding to the relative radiant energy ϵ_2 from the radiation function.

It is difficult, if not impossible, to derive a closed-form expression for the radiation function and the film response function. Therefore, for convenience, the computer program uses tabular representations of the two functions. For both functions the independent variable is defined to be energy (either surface radiant energy or film exposure energy). The values of independent variable (energy) are established at arbitrary increments for both functions. The actual values of the increments are immaterial, so only the corresponding values of dependent variable (temperature for the radiation function and density for the film response function) are stored. Intermediate values of the dependent variables must be determined by interpolation.

Lagrangian polynomial interpolation was selected, and for simplicity a formula was used that required monotonically increasing values of the independent variable at arbitrary intervals. For those cases in which the succeeding values of the independent variable are decreasing, their reciprocals are used. The formula for arbitrary spacing was used because on occasion an inverse interpolation must be performed (e.g., a value of energy must be found that corresponds to a value of temperature). Out-of-range arguments return the appropriate lowest or highest value, with an error message, but do not interrupt program execution.

The film response function is illustrated in figure 1 in terms of relative log film density against relative film exposure energy. However, it is not used that way in the computer program. The image analysis system measures transmittance rather than density. The values of transmittance fall on an arbitrary scale between 0 and 225. The function produced by the system is represented by figure 5. If desired, the function illustrated in figure 1 can be derived from that illustrated in figure 5 by measuring the brightness values of the image of a calibrated stepped-exposure scale. Figure 6 shows such a scale for the values of system parameters used in this test. The parameters are magnification, effective lens aperture, and amplifier gain. Different values of these parameters affect the form of this function, and sometimes produce a nonlinear function. The parameters for this test were deliberately chosen to produce a nearly linear representation of this function. However, it is emphasized that this function is used only implicitly in the procedure described herein. It is derived only to ascertain that it is nearly linear. The function illustrated in figure 5 is the one used.

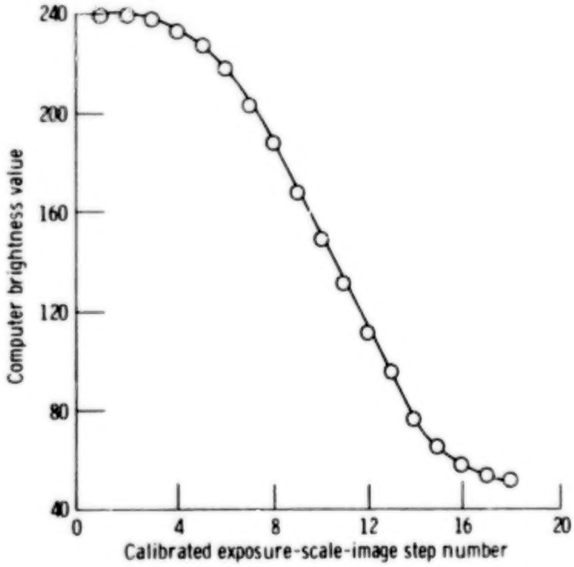


Figure 5. - Computer representation of film response function.

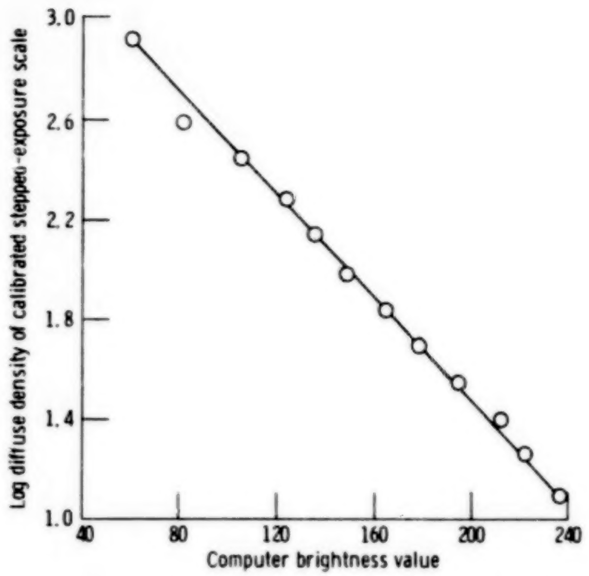


Figure 6. - Calibration of computer brightness values for an arbitrary magnification, effective aperture, and amplifier gain.

Figure 7. - Temperature function.

Figure 7 shows the temperature function derived from figures 1 and 3 for a given reference value of temperature and density. Again, this function is not explicitly derived in the computer program but is shown here for illustration.

Application to Turbine Blade

The nominal dimensions of the blade and its images are given in table I. The critical information is

TABLE I. - BLADE OR IMAGE DIMENSIONS

	Film image	Blade	Video image
	Nominal dimensions, mm		
Ratio	1	6	18
Span	8	50	150
Chord	6	34	100
Vertical aperture	.16	1	3
Horizontal aperture	.2	1.3	4

that the ratio of the dimensions on the film, the actual blade dimensions, and the dimensions on the television monitor is approximately 1:6:18. The vertical side of the television image consists of 490 lines. The vertical dimension is approximately 215 millimeters. The aspect ratio is the standard 3:4, vertical to horizontal. The system is capable of selecting any given picture element by means of the joystick-operated cursor. Therefore the minimum television aperture that can be resolved is approximately 0.44 millimeter vertically by 0.58 millimeter horizontally. This corresponds to approximately 0.15 millimeter by 0.19 millimeter on the blade and to approximately 0.025 millimeter by 0.03 millimeter on the film image. For a number of reasons it is impractical to use such a small aperture for measuring the density at any given point on the film image.

First, those dimensions are of the same order of magnitude as the limit of resolution of the film-lens system. Second, film granularity and electronic noise introduce measurable point-to-point variations in density on this scale. Therefore it is desirable to use a density-measuring aperture several times the size of this minimum. Obviously, the larger the factor, the greater the smoothing effect, but the less sensitive the system is to variations in density. Furthermore the larger factor increases the time required for computer processing. A trial-and-error procedure resulted in

the choice of seven picture elements in each direction. This means that at any given location defined by the cursor or derived from coordinates computed by the computer program, the density was averaged over 49 elements. They were arranged in a square with three elements above, below, and to each side of the element in question. The rectangular dimensions resulted from the 3:4 aspect ratio of the standard television image. This produced an effective aperture of approximately 1 millimeter by 1.3 millimeters on the blade for the video densitometry system.

Comparison of Results

It is essential to demonstrate that the results produced by the video densitometry method agree with those produced by the microdensitometry method of infrared photographic pyrometry. To test for agreement, an image of a heated turbine blade was analyzed by both methods. The temperatures were measured on a coordinate system defined by five equally spaced positions along the chord and seven equally spaced positions along the span. Figure 8 shows the turbine blade, and figure 9 shows the coordinate system. One of the coordinate lines was along the midspan. The chordal positions included the leading and trailing edges. The effective apertures for both methods were approximately equal. All calibrations and analyses in both methods were conducted as described in the preceding sections of this report. The results of the comparison are presented in table II. The results along the midchord are plotted in figure 10.

Note that the greatest difference between the two methods is 15 degrees C and that the average difference is approximately 2 degrees C.

The reproducibility of results from both methods depends more on the precise locations of the coordinates than on any other factor. This is especially evident in regions of high temperature gradient. In these tests the regions of greatest thermal gradient corresponded to the regions of highest temperature. A straightforward extension of this line of reasoning leads to the conclusion that the difference between the results produced by the two methods is greatest in regions of greatest thermal gradient.

In both methods deliberate misplacement of the coordinate system produced the results described above. The same film frame was analyzed several times by each method. In some cases care was exercised to locate the origin of the coordinate system as precisely as possible. In other cases the origin was deliberately displaced. It was always easier to locate the origin by the video system than by the manual system. With care the maximum temperature difference on successive trials could be kept to within 5 degrees C by the video method, with no differences in

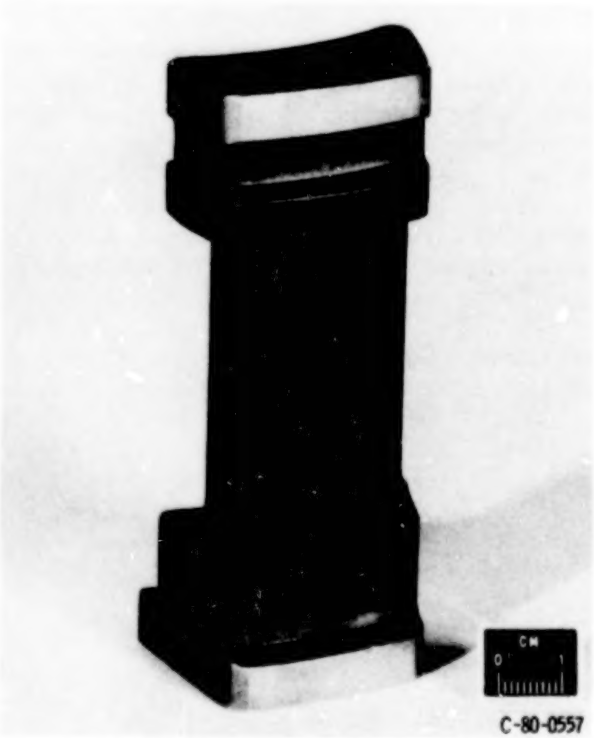


Figure 8. - Turbine blade used for comparison of methods.

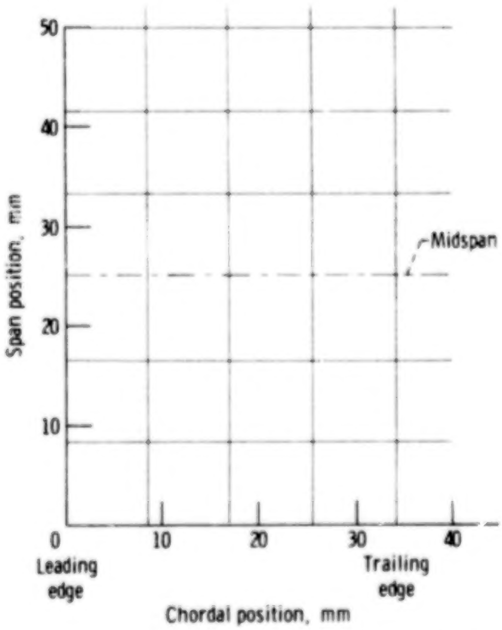


Figure 9. - Coordinate system used for comparison of methods (projection).

TABLE II. - MANUAL AND COMPUTERIZED RESULTS FROM GRID IN FIGURE 9

Turbine blade span position, mm	Turbine blade chordal position, mm														
	0			8			17			26			34		
	By video method	By manual method	Difference	By video method	By manual method	Difference	By video method	By manual method	Difference	By video method	By manual method	Difference	By video method	By manual method	Difference
	Temperature, °C														
50	835	830	5	820	820	0	790	790	0	770	775	-5	755	770	-15
42	940	955	-15	885	885	0	845	850	-5	825	830	-5	810	825	-15
33	970	975	-5	905	905	0	880	865	15	860	855	15	850	840	10
25	980	970	10	910	905	5	880	875	5	870	860	10	855	850	5
16	950	[illegible]	10	900	885	15	875	865	10	865	855	10	855	850	↓
8	900	890	10	870	865	5	850	850	0	845	845	0	840	835	↓
0	815	810	5	805	810	-5	790	800	[illegible]	785	785	0	765	760	↓

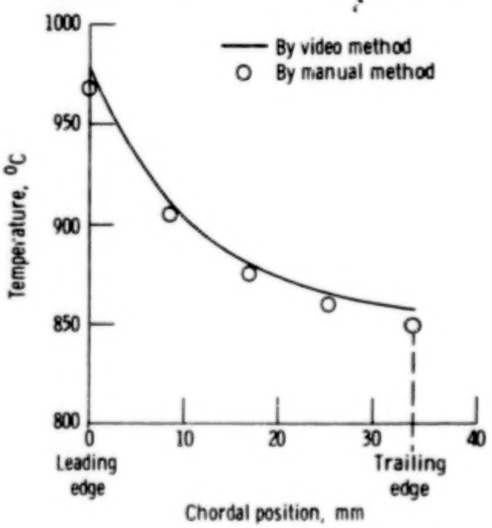


Figure 10. - Comparison of results across mid-span on typical blade.

the low-temperature region. The final conclusion is that, where there are differences between the results produced by the two methods, greater confidence can be placed in those produced by the video densitometry method. The reason is that the entire image is displayed at a moderate magnification on the video monitor but only a small portion of the image is visible on the microdensitometer. The blade image can be easily alined with previously defined reference lines by eye. Therefore the origin of the desired coordinate system should be located with greater precision.

Conclusions

A computerized video densitometry procedure has been developed for rapid and accurate determination of the temperature distribution across a heated surface from infrared photographs. The results compare favorably with, and are more reproducible than, those produced by the manual densitometry method. Moreover, these results are produced approximately 50 times faster than possible with the manual method. The combination of speed, freedom from random errors in computer produced results, and magnetic tape output makes it possible to use these results as input to another computer program. It is anticipated that such will be the case in a computation of life prediction for aircraft gas turbine blades.

The procedure has been illustrated on one of the aircraft gas turbine blades planned for use in the aforementioned life prediction study. It is anticipated that the total analysis will require approximately 20 man-hours, as compared with 1000 man-hours by the manual method. Furthermore data entry for the succeeding computer analysis is greatly simplified and a potential source of error is eliminated. Greater understanding of the effect of various blade cooling configurations will result from plots of the temperature distributions. Such plots can be produced automatically by a computer by using the magnetic tape as input data.

Lewis Research Center
National Aeronautics and Space Administration,
Cleveland, Ohio, February 20, 1980,
505-01.

Appendix – Computer Program

A simplified flow diagram of the computer program is illustrated in figure 11. The program is interactive and under complete control of the operator. Upon entry the operator is prompted by English language queries and controls the program with English language responses.

The radiation function is evaluated externally and compiled into the program as an unchanging table of data. All the other data can be regenerated as desired and remain stored on a system disk until changed. Upon entry the program flow can be directed along any one of five paths. Initially the paths are taken in the order shown in figure 11, from top to bottom: namely, definition of coordinates, film response function, reference density and temperature, and temperature measurement. The last operation is performed repeatedly for a single value of the other functions. However, any one of those functions may be redefined whenever necessary without disturbing the others.

The coordinates are defined with use of the joystick-operated cursor. A film image is digitized, and the positions at which it is desired to measure temperature are read from the cursor position. When the other functions are performed, a reference grid is drawn on the monitor to insure proper location and orientation of the image. All coordinates are located with respect to the trailing edge of the blade image. Therefore, its location is obtained as a reference, by using the cursor, in this and succeeding operations.

The film response function is obtained from an image of a calibrated stepped-exposure scale. The reference temperature and density are acquired from a specified steady-state image. The temperature has been obtained previously from an optical pyrometer. The image is digitized, and a portion of it is scanned for the maximum density. The region to be scanned is defined by the cursor.

The reference temperature produces a corresponding value of surface radiant energy from the radiation function, and the reference density produces a corresponding value of film exposure energy from the film response function. The difference between these values is stored for "aligning" the two functions when they are used for temperature measurement.

The desired temperatures are obtained quite simply. An image is alined with reference lines drawn on the monitor. The image is then digitized, and its trailing edge is located with the cursor. At each of the predefined coordinates the density is determined, and its corresponding temperature is calculated from the film response function and the radiation function. The temperatures are stored in a table, which is displayed on the console terminal at the conclusion of the operation, and are written on magnetic tape for input to future computer programs.

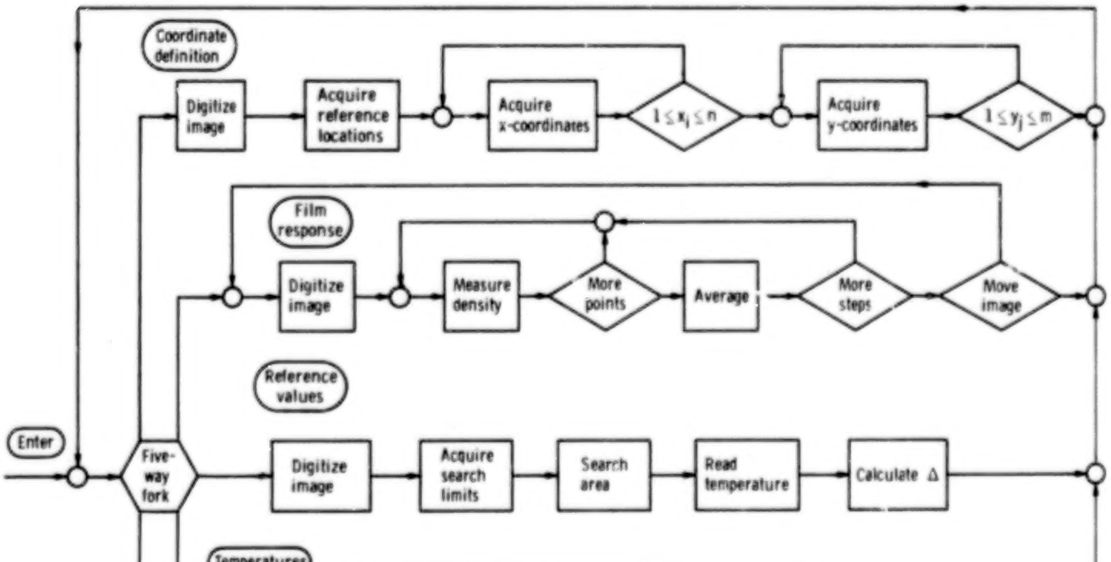


Figure 11. - Simplified flow chart of computer program.

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15. Supplementary Notes

16. Abstract

A computerized video densitometry method for the rapid analysis of thermal data from infrared photographs is described. It is approximately 50 times faster than a corresponding manual method of analysis, with no apparent sacrifice of accuracy. The object of the technique is to determine the temperature distribution across a heated surface. Infrared photographs of the heated surfaces provide the raw data. A video-based, computer-operated image analysis system provides the equipment. Infrared photographic pyrometry using a flat-bed microdensitometer forms the basis of the technique. The procedure is illustrated on a thermally cycled aircraft gas turbine blade.

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